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Assessing environmental consequences of using co-products in animal feed

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Abstract

Purpose The livestock sector has a major impact on the environment. This environmental impact may be reduced by feeding agricultural co-products (e.g. beet tails) to livestock, as this transforms inedible products for humans into edible products, e.g. pork or beef. Nevertheless, co-products have different applications such as bioenergy production. Based on a framework we developed, we assessed environmental consequences of using co-products in diets of livestock, including the alternative application of that co-product.

Methods We performed a consequential life cycle assessment, regarding greenhouse gas emissions (including emissions related to land use change) and land use, for two case studies. Case 1 includes increasing the use of wheat middlings in diets of dairy cattle at the expense of using it in diets of pigs. The decreased use of wheat middlings in diets of pigs was substituted with barley, the marginal product. Case 2 includes increasing the use of beet tails in diets of dairy cattle at the expense of using it to produce bioenergy. During the production of biogas, electricity, heat and digestate (that is used as organic fertilizer) were produced. The decrease of electricity and heat was substituted with fossil fuel, and digestate was substituted with artificial fertilizer.

Results and discussion Using wheat middlings in diets of dairy cattle instead of using it in diets of pigs resulted in a reduction of 329 kg CO_2 eq per ton wheat middlings and a decrease of 169 m^2 land. Using beet tails in diets of dairy cattle instead of using it as a substrate for anaerobic digestion resulted in a decrease of 239 kg CO_2 eq per ton beet tails and a decrease of 154 m^2 land. Emissions regarding land use change contributed significantly in both cases but had a high uncertainty factor, ±170 ton CO_2 ha^{-1}. Excluding emissions from land use change resulted in a decrease of 9 kg CO_2 eq for case 1 'wheat middlings' and an increase of 50 kg CO_2 eq for case 2 'beet tails'.

Conclusions Assessing the use of co-products in the livestock sector is of importance because shifting its application can reduce the environmental impact of the livestock sector. A correct assessment of the environmental consequences of using co-products in animal feed should also include potential changes in impacts outside the livestock sector, such as the impact in the bioenergy sector.

Keywords Bioenergy · Consequential LCA · Co-product · Dairy cattle · Land use change · Livestock feed · Pigs

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1 Introduction

Current livestock production levels pose severe pressure on the environment via their emissions to air, water and soil (Tilman et al. 2001; Steinfeld et al. 2006). The livestock sector also competes increasingly for scarce resources such as land, water and fossil energy (Steinfeld et al. 2006; De Vries and De Boer 2010). The challenge, therefore, is to reduce emissions to the environment and to increase efficient use of scarce resources per kilogram of animal-source food produced. The environmental impact of livestock production results mainly from production and utilization of feed (Van der Werf et al. 2005; Elferink et al. 2008; De Vries and De Boer 2010). A

possible way to reduce the impact of livestock production is feeding co-products from, for example, arable production or the food processing industry to livestock. Examples of co-products are wheat middlings, a co-product from wheat cultivated to produce wheat flour, or beet tails, a co-product from sugar beets cultivated to produce sugar. As most emissions or resources used, for example during crop cultivation or processing, are ascribed to the main product that economically drive these production stages, the environmental impact of an untreated co-product is according to Elferink et al. (2008) relatively low. Furthermore, most co-products are inedible for humans or do not meet Dutch food requirements, such as taste and texture. Therefore, feeding co-products to livestock transforms an inedible product into an edible product, such as meat, milk and eggs (Fadel 1999; Elferink et al. 2008; Garnett 2009).

Some co-products are used in diets of livestock (Nonhebel 2007; Elferink et al. 2008; Vellinga et al. 2009). Vellinga et al. (2009) showed that in the Netherlands in 2007, the amount of co-products used in diets of livestock was 22 %. The current motivation to use co-products in diets of livestock, however, depends on a combination of their nutritional value and cost price, and is not driven by environmental motives. Elferink et al. (2008) concluded that for all Dutch citizens about 81 g of pork per day can be produced, while using all co-products from the sugar beet, vegetable oil, and potato industry, which represent approximately 60 % of the co-products produced from the food industry in the Netherlands. When corrected for the total share of co-products in feed produced in the Netherlands, enough pig meat can be produced to fulfil the amount of animal protein advised by the Dutch health organizations, while the environmental impact per kilogram of meat produced decreased (Elferink et al. 2008). However, we should take into account that, besides feed, co-products might have other applications, such as production of bioenergy, or can be fed to other species. Increasing the use of a co-product in animal feed inherently implies decreasing the availability of that co-product for other applications as the production of the co-product is determined by the main product that economically drives the production stages. In the Netherlands, for example, there is a competition between animal feed and bioenergy production for wet co-products, such as beet tails and potato peels (Koppejan et al. 2009). Increasing the use of co-products in the livestock sector, therefore, may have an environmental impact on processes outside the production cycle of the livestock sector, e.g. on processes in the bioenergy industry. That impact needs to be considered when evaluating the environmental impact of using co-products in the livestock sector.

The goal of this paper was to assess the overall environmental consequences of increasing the use of co-products in diets of livestock, including environmental consequences for the alternative application of that co-product. We used consequential life cycle assessment (CLCA) to illustrate the overall consequences for two Dutch case studies, regarding global warming potential (GWP) and land use (LU). In the first case, we analyzed the consequences of increasing the use of wheat middlings in diets of dairy cattle at the expense of using it in diets of pigs, whereas in the second case, we analyzed the consequences of increasing the use of beet tails in diets of dairy cattle at the expense of using it to produce bioenergy. These cases were of interest as both co-products are used as energy source in livestock feed and, therefore, are comparable with respect to feed requirements. Furthermore, both co-products are used as dairy cattle feed but they differ in their alternative application. Wheat middlings are used in pig feed but can be used in dairy cattle feed as well. Beet tails are used in the bioenergy sector (De Vries et al. 2012b) but can be used in dairy cattle feed as well.

2 Methods

2.1 Consequential life cycle assessment

Life cycle assessment (LCA) is an internationally accepted and standardized holistic method (ISO14040 1997; ISO14041 1998; ISO14042 2000; ISO14043 2000) to evaluate the environmental impact during the entire production chain (Guinée et al. 2002; Bauman and Tillman 2004). In this study, we focussed on LU and GWP (including emissions from land use change (LUC)).

Two types of LCA exist: attributional LCA and CLCA. Attributional LCA describes the environmentally relevant physical flows to and from a product or process, while CLCA describes how environmental flows change in response to a change in the system (Ekvall and Weidema 2004). As our aim was to determine environmental consequences of a change in use of co-products, we performed a consequential LCA.

The starting point in our CLCA was a multifunctional process, an activity that fulfils more than one function (Ekvall and Finnveden 2001), yielding two products: the determining product, which determines the production volume of that process, and a co-product (Weidema et al. 2009). A change in demand of the determining product directly affects the production volume of the co-product, and subsequently the production of the product that is displaced by that co-product (Weidema et al. 2009). Within CLCA, system expansion is generally used to deal with multifunctional processes. System expansion implies that you include changes in the environmental impact of the alternative production process, for which the co-product could be used, into your analysis by subtracting the impact related to the alternative production process (Ekvall and Finnveden 2001). Weidema et al. (2009) developed a framework to ascribe the environmental impact of a multifunctional process to various outputs, based on system

expansion. Their framework, however, was based on the assumption that the demand for the determining product or co-product increased or, in other words, the total amount of available co-product increased. In our analysis, however, we assumed a stable market situation. We wanted to assess the consequences of changing the application of a co-product, while the demand remained equal. When the demand for both the determining product and co-product remained equal, the total amount of available co-product remained equal as well. In this way, we could analyze what the optimal use of a co-product is from an environmental perspective. Therefore, we extended the framework of Weidema et al. (2009) to allow an analysis of the environmental consequences of a change in application of a co-product, for example, a change from application in bioenergy production to application in diets of livestock. The extended framework is explained in Section 2.4.

2.2 Case description

Two co-products, i.e. wheat middlings and beet tails, were selected as cases to illustrate our extended framework.

2.2.1 Case 1: wheat middlings

Milling of wheat results in the production of wheat flour used for human consumption (the determining product) and wheat middlings (the co-product). The production volume of wheat middlings, therefore, is determined by the demand for wheat flour.

In this case study, we illustrated the environmental consequences of increasing the use of wheat middlings with one ton in diets of dairy cattle while the number of animals remained equal. We assumed that an increased use of wheat middlings in diets of dairy cattle inherently implied a decreased use of wheat middlings in diets of pigs. Wheat middlings are used in dairy cattle feed and pig feed for their energy content. The decreased use of wheat middlings in diets of pigs must be substituted with an alternative product while the number of pigs remained equal. The marginal energy-rich fodder was assumed to be barley produced in the Netherlands (Weidema 2003). Wheat middlings and barley are both products with a high energy and low protein content.

2.2.2 Case 2: beet tails

Beet tails (the co-product) are cut off after first cleaning (screening and washing) of sugar beets during the production of sugar (the determining product). The production volume of beet tails, therefore, is determined by the demand for sugar.

In this case study, we illustrated the environmental consequences of increasing the use of beet tails with one ton in dairy cattle feed while the number of animals remained equal. Beet tails are used in dairy cattle feed for their energy content, but can alternatively be used for production of bioenergy. During the conversion of biomass by anaerobic digestion into biogas, methane (CH_4), carbon dioxide (CO_2) and trace gases (e.g. hydrogen gas) are produced, which can be used to produce bioenergy in the form of electricity, heat or transport fuel (Hamelin et al. 2011; De Vries et al. 2012a). The remaining product after digestion is called 'digestate' and can be used as organic fertilizer replacing artificial fertilizer (Börjesson and Berglund 2007). We assumed that an increased use of beet tails as dairy cattle feed inherently implied a decreased use of beet tails for bioenergy production. The decreased production of electricity, heat and digestate must be substituted with an alternative product, i.e. the marginal product. Electricity was assumed to be substituted with marginal Dutch electricity, i.e. 28 % coal-based, 67 % natural gas-based and 5 % wind-based electricity (De Vries et al. 2012a). Fifty percent of the heat was assumed to be substituted with marginal heat, i.e. 79 % natural gas-based and 21 % light fuel oil-based in the Netherlands. The rest is used for digestion processes and therefore no alternative products were included (De Vries et al. 2012a). The digestate that is transported and applied to the field as fertilizer was assumed to be substituted by marginal mineral N, P and K fertilizer. Marginal production of mineral fertilizer was assumed to be calcium ammonium nitrate for N, triple superphosphate for P_2O_5 and potassium chloride for K_2O (De Vries et al. 2012a).

2.3 Environmental consequences

We assessed the consequences of a change in co-product use for greenhouse gas (GHG) emissions and LU. Emission of GHGs and LU were chosen as an example as the livestock sector has a significant contribution to both climate change and LU worldwide (Steinfeld et al. 2006). Emissions of GHGs regarding LUC were included, but reported separately. The following GHGs were included: CO_2, CH_4 and nitrous oxide (N_2O). We assessed the change in global warming potential per ton co-product, i.e. wheat middlings or beet tails, by summing up changes in emissions of these GHGs based on their equivalence weighting factors in terms of CO_2 (100 years' time horizon): i.e. 1 for CO_2, 25 for CH_4 and 298 for N_2O (Forster et al. 2007).

GHG emissions associated with the production of beet tails and barley were based on data of De Vries et al. (2012b). LUC and LU data related to the cultivation of barley were based on Tonini et al. (2012) and De Vries et al. (2012b). When computing LUC, we focused on the cultivation of barley only and excluded low land use processes such as transport. Tonini et al. (2012) quantified CO_2 emissions of converting, for example, forest or grassland to cropland, accounting for size and location of converted land and the types of land that were converted (biome types). De Vries et al. (2012b) assumed that

1.22 ha of land needed to be converted somewhere in the world to compensate for the use of 1 ha (average Dutch yield) of barley in the Netherlands. A LUC emission factor of 310 ton $CO_2 ha^{-1}$ of displaced barley was derived, with an uncertainty of ±170 ton $CO_2 ha^{-1}$ (Tonini et al. 2012). This corresponds to 1.55 kg $CO_2 m^{-2}$ year^{-1} (±0.84 kg $CO_2 m^{-2}$ year^{-1}) with an amortization period of 20 years (as prescribed in the Renewable Energy Directive (EU 2009)).

2.4 Framework

Figure 1 illustrates our extended framework (based on Weidema et al. 2009). The terminology used in this chapter and figures were based on Weidema et al. (2009), as we extended their framework.

The multifunctional process was denoted as *process A*, where product A was the determining product. The *process* described the environmental impact related to the product. The *process* is referred to in italics. *Process B* was the process related to the use of the co-product. The intermediate process (*process I*) was a process or series of processes between the point where the co-product left the process route of the determining product and its use in *process B*. The product produced during this intermediate process was defined as intermediate product (product I). In case product I was not available for *process B*, another product, i.e. product D, was used. Use of product I in *process B*, therefore, displaced use of product D. The difference in environmental impact in *process B* due to using product I instead of product D was denoted by Δ*B*. If a co-product was not fully used, it went to waste treatment, *process W*.

Figure 1 shows the environmental consequences of three possible changes in application of a co-product. These three situations are explained below.

2.4.1 Situation 1: changing the application of a co-product

Situation 1, i.e. changing the application of a co-product from *process B1a* to *B1b*, corresponds with the first case: wheat middlings fed to dairy cattle instead of pigs. The environmental impact of this change in application is determined as:

$$D1a - \Delta B1a - D1b + \Delta B1b. \tag{1}$$

Parameters are explained in the following paragraphs.

Computing D1a and D1b D1a is the environmental impact related to the production of product D1a that is needed to replace product I in *process B1a*. To quantify *D1a* in our case of wheat middlings, we needed to determine the amount of

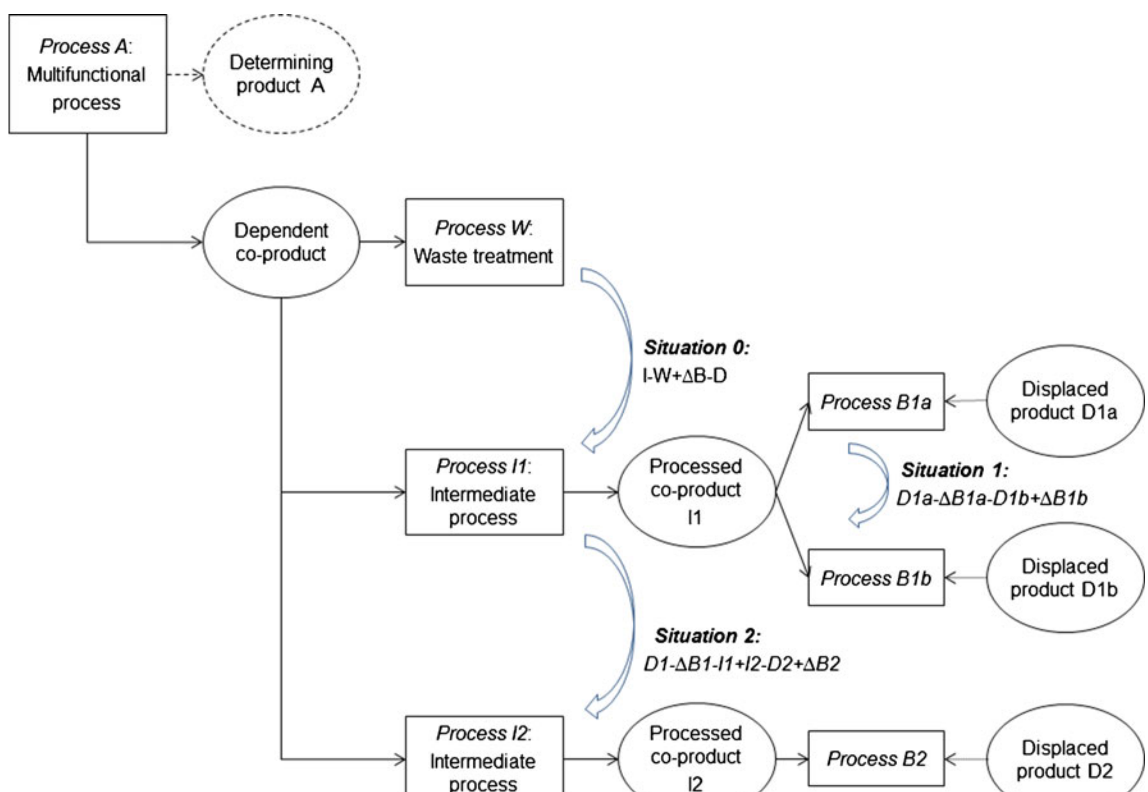

Fig. 1 Framework for assessing environmental consequences of changing the application of co-products in diets of livestock while the production of product A and B remains the same, three different situations (based on Weidema et al. 2009)

barley required to replace 1 kg of wheat middlings in pig feed, and the environmental impact and LU of producing 1 kg of barley. Wheat middlings and barley were assumed to be exchanged on the basis of their net energy content. The available net energy in pig feed is expressed in EW (in Dutch, Energie Waarde (energy value)). The EW of wheat middlings and barley were obtained from the feed tables of the Dutch Central Bureau for Livestock Feeding (CVB 2010). Wheat middlings contain 0.75 EW per kg, whereas barley contains 1.05 EW per kg. To replace 1 kg of wheat middlings in pigs feed, we need 0.71 kg barley. Given a dry mater (DM) content of barley of 86.9 %, 621 kg of DM barley was needed to replace 1 ton of wheat middlings (i.e. 0.71 kg barley × 0.869 × 1,000 = 621 kg). The production of 1 kg DM barley results in 0.44 CO_2 eq (excl. LUC) and a land use of 1.60 m^2 (De Vries et al. 2012b).

D1b is the environmental impact related to the production of product D1b that is avoided because of the use of product I in *process B1b*. To quantify *D1b* in our case of wheat middlings, we needed to determine the amount of barley avoided per kilogram of wheat middlings in dairy cattle feed, and the environmental impact and LU of 1 kg of barley (similar as *D1a*). Just like for pigs, barley and wheat middlings were assumed to be exchanged in diet of dairy cattle on the basis of their net energy content. In the Netherlands, the available net energy in dairy cattle feed is expressed in VEM (In Dutch, Voeder Eenheid Melk (fodder unit milk)). Wheat middlings contains 815 VEM per kg, whereas barley contains 975 VEM per kg (CVB 2010). To replace 1 kg of wheat middlings in diets of dairy cattle, we needed 0.84 kg of barley. Given a DM content of barley of 86.9 %, 726 kg of DM barley was needed to replace 1 ton of wheat middlings (0.84 kg barley × 0.869 × 1,000 = 726 kg).

Computing ΔB1a and ΔB1b *ΔB1a* is the difference in environmental impact of *process B1a*, i.e. feed utilization of a pig when feeding wheat middlings instead of barley. During the digestive process, ruminants, and to a minor extent monogastric animals, emit CH_4 (Steinfeld et al. 2006). Changing the diet to a higher fibre composition can increase the enteric fermentation of pigs (Jensen and Jørgensen 1994). In total, however, CH_4 emission from enteric fermentation of pigs is only 0.2 million ton per year compared to 2.19 for dairy cattle and 2.31 for other cattle in western Europe (Steinfeld et al. 2006). Based on these numbers, we assumed that the difference in enteric CH_4 emission produced when barley instead of wheat middlings were used in diet of pigs only slightly affected emissions from *process ΔB1a* and, therefore, Δ*B*1*a* was set to zero.

ΔB1b is the difference in environmental impact of *process B1b*, i.e. feed utilization of a cow when feeding barley instead of wheat middlings. In dairy farming, CH_4 contributes approximately 52 % to total GHG emissions in the chain, mostly caused by enteric fermentation processes within the cow (Gerber et al. 2010). As the amount of enteric CH_4 is related to the type and amount of feed (Dijkstra et al. 2007; Beauchemin et al. 2008; Ellis et al. 2008), we assumed a change in enteric CH_4 emission by dairy cattle due to feeding wheat middlings instead of barley (i.e. Δ*B1b*). This change in enteric CH_4 emission can be computed by using IPCC Tier 2 or IPCC Tier 3 approach (IPCC 2006). IPCC Tier 2 assumed that 6.5 % of gross energy intake is converted to CH_4 (IPCC 2006). As we exchanged beet tails and barley on the basis of their energy intake, no difference would be found. We, therefore, preferred IPCC Tier 3, which advices to use more specific data when possible. Based on empirical relationships between dry matter intake of different feed ingredients and CH_4 emission factors per ingredient, enteric CH_4 from dairy cattle was calculated. We adapted CH_4 emission factors per feed ingredient from Vellinga et al. (2013), which are based on a mechanistic model originating from Dijkstra et al. (1992), and updated by Mills et al. (2001) and Bannink et al. (2006). For wheat middlings, enteric CH4 emission was assumed to be 20.34 g/kg DM (DM content is 86.5 %), and for barley 22.17 g/kg DM (Vellinga et al. 2013).

2.4.2 Situation 2: changing the application and the intermediate treatment

Situation 2, i.e. changing the application from *B1* to *B2* and the intermediate process of a co-product from *process I1* to *I2*, corresponds with the second case: beet tails fed to dairy cattle instead of using it as a substrate for anaerobic digestion. The environmental impact of this change in application and intermediate process is determined as:

$$D1 - \Delta B1 - I1 + I2 - D2 + \Delta B2. \quad (2)$$

Parameters are explained in the following paragraphs.

Computing D1 and D2 *D1* is the environmental impact related to the production of product D1 that is needed to replace product I1 in *process B1*. In our case of beet tails, multiple products are produced during the production of bioenergy and, therefore, D1 consists of two components: a and b (Fig. 3). To quantify *D1*, we needed to determine the amount of marginal fossil-based electricity, heat (*D1a*) and artificial fertilizer (*D1b*) required to replace the bioenergy produced and fertilising capacity provided by 1 kg of beet tails and the resulting digestate. Accordingly, the environmental impact of producing these marginal products was included. Electricity and heat produced from bioenergy, and electricity and heat produced from fossil sources were exchanged on the basis of an equivalent amount of MJ. Electricity and heat produced

from bioenergy, and electricity and heat produced from fossil sources were exchanged on the basis of an equivalent amount of MJ. Digestate produced during the production of bioenergy and artificial fertilizer was exchanged on the basis of the N, P and K fertilizer replacement value. The N fertilizer replacement value for digestate was assumed to be 65 % and for artificial fertilizer 100 % (DR 2012). Based on De Vries et al. (2012a), we assumed that the replacement value for P and K was 100 % for all products. With 1 ton of beet tails, 459 MJ electricity, 240 MJ heat (i.e. 50 % of the surplus heat produced) and 1.45 kg N (2.23×0.65), 0.70 kg P and 2.30 kg K in digestate, were produced (De Vries et al. 2012b). The emissions and LU data for heat and electricity production from fossil energy and artificial fertilizer production were taken from the Ecoinvent database v2.2 (EcoinventCentre 2007).

D2 is the environmental impact related to the production of product D2 that is avoided because of the use of product I2 in *process B2*. To quantify *D2* in our case of beet tails, we needed to determine the amount of barley avoided per kilogram of beet tails in dairy cattle feed, and the environmental impact and LU of barley (similar as in case 1). Just like for case 1, barley and beet tails were assumed to be exchanged in dairy cattle feed on the basis of their net energy content. Beet tails contain 106 VEM per kg, whereas barley contains 975 VEM per kg (CVB 2010). To replace 1 kg of beet tails in diets of dairy cattle, we needed 0.11 kg of barley. Given a DM content of barley of 86.9 %, 94 kg of DM barley was needed to replace 1 ton of beet tails (0.11 kg barley×0.869×1,000=94).

Computing ΔB1 and ΔB2 *ΔB1* is the difference in environmental impact of *process B1*, i.e. application of fertilizer (*ΔB1a*), electricity and heat (*ΔB1b*). We assumed that using electricity and heat produced from fossil sources instead of bioenergy will not have any impact. However, the difference in emissions during the application of artificial fertilizer instead of digestate has to be accounted for. Emission and LU of the application of 1 kg digestate and artificial fertilizer were based on data of EcoinventCentre (2007) and De Vries et al. (2012b).

ΔB2 is the difference in environmental impact of *process B2*, i.e. feed utilization of a cow. For dairy cattle, similar to the first example, the approach of Vellinga et al. (2013) was used. One kilogram beet tails DM (DM content is 13.6 %) caused 20.00 g CH_4 emission (Vellinga et al. 2013).

Computing I1 and I2 *I1* is the environmental impact related to the production of product I1. Intermediate processes related to the production of bioenergy were transport of beet tails from the sugar factory to the bioenergy installation, digestion of beet tails, storage and transport of digestate, and burning of bioenergy.

I2 is the environmental impact related to the production of product I2. The only intermediate process was the transport of the beet tails from the sugar fabric to the dairy cattle farm.

Emissions and LU data were taken from the EcoinventCentre v2.2 (EcoinventCentre 2007) and were based on De Vries et al. (2012b).

2.4.3 Situation 0: a co-product that currently goes to waste will be applied in a production process

Situation 0 is changing from *process W* to *process I*. Situation 0, however, only occasionally occurs in the livestock sector because most co-products used in animal feed already had an application. We, therefore, did not further elaborate on this situation with a case but only described the affected processes. The environmental impact of situation 0 is determined as:

$$I - W + \Delta B - D. \qquad (3)$$

I is the environmental impact related to the production of product I, i.e. potato peels as feed ingredient. The volume of the intermediate treatment will increase, resulting in an increase of emissions from the intermediate process (*I*). *W* is the environmental impact related to waste treatment. The volume of waste treatment will decrease *ΔB* is the change in environmental impact of *process B* due to using product I instead of product D. *D* is the environmental impact related to the production of product D. The volume of product D that fulfilled the application before product I will decrease.

3 Results and discussion

3.1 Results case study 1: wheat middlings fed to dairy cattle instead of pigs

3.1.1 Changes in land use

Changes in LU from using 1 ton wheat middlings in dairy cattle feed instead of in pig feed were based on Eq. [1]: $D1a - \Delta B1a - D1b + \Delta B1b = 996 - 0 - 1{,}165 + 0 = -169$ m^2 (Fig. 2).

Displacing 1 ton wheat middlings in pig feed required an additional production of 621 kg of DM barley, resulting in an increase of 996 m^2 (*D1a*). Using 1 ton wheat middlings as dairy cattle feed, however, displaced 726 kg of DM barley in dairy cattle feed, resulting in a decrease of 1,165 m^2 (*D1b*). No LU was related to *ΔB*. This means in our case study that land use was decreased with 169 m^2 when 1 ton of wheat middlings was used in dairy cattle feed instead of in pig feed.

3.1.2 Changes in emission of GHGs

Changes in emission of GHGs from using 1 ton wheat middlings in dairy cattle feed instead of in pig feed were based on Eq. [1]: $D1a - \Delta B1a - D1b + \Delta B1b = 273 - 0 - 320 + 37 = -9$ kg CO_2 eq.

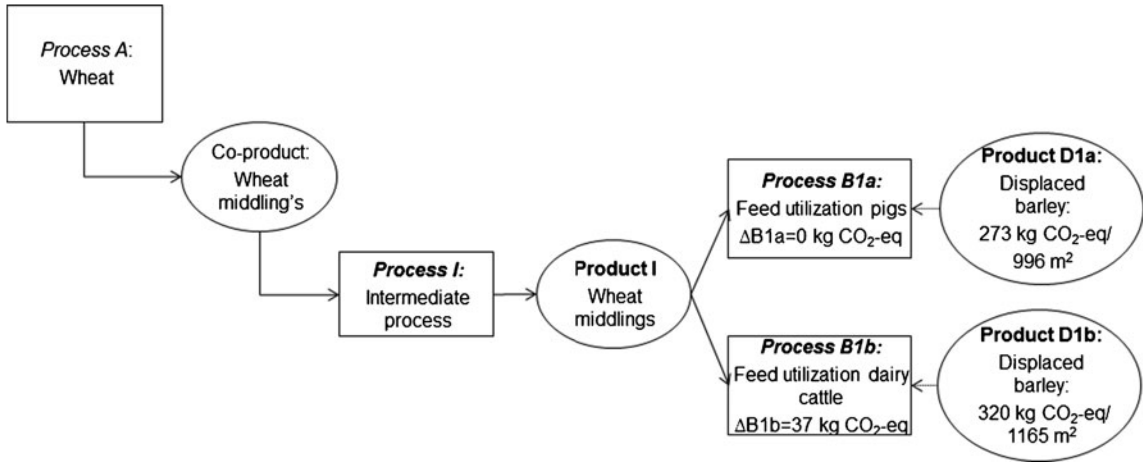

Fig. 2 Processes that are affected by using 1 ton of wheat middlings as dairy cattle feed instead of using it as pig feed (situation 1, Eq.: $D1a-\Delta B1a-D1b+\Delta B1b$)

Displacing 1 ton wheat middlings in pig feed required an additional production of 621 kg of DM barley resulting in an increase in GHG emission of 273 kg CO_2 eq (*D1a*). Using 1 ton wheat middlings as dairy cattle feed, however, displaced 726 kg DM barley in dairy cattle feed resulting in a decrease of 320 kg CO_2 eq (*D1b*).

GHG emission related to feed utilization (i.e. CH_4 from enteric fermentation) was 0 for pigs ($\Delta B1a$) and 37 kg CO_2 eq for dairy cattle ($\Delta B1b$). The latter value was computed given that 1 ton of wheat middlings as dairy cattle feed displaced 726 kg DM barley resulting in the emission of 16.10 kg CH_4 (i.e.$726\times22.17/1{,}000$), whereas 1 ton of wheat middlings (865 kg DM) resulted in the emission of 17.59 kg CH_4 (i.e. $865\times20.34/1{,}000$). Therefore, enteric CH_4 emission was increased with 1.49 kg CH_4, resulting in 37 kg CO_2 eq by feeding wheat middlings instead of barley to dairy cattle.

This means, in our case study, that using 1 ton of wheat middlings in dairy cattle feed instead of in pig feed decreased GHG emissions by 9 kg CO_2 eq. When accounting for GHG emissions from LUC (i.e. $1.22\times1.55\times169$ m^2=−319 kg CO_2 eq), using 1 ton of wheat middlings in dairy cattle feed instead of in pig feed reduced emissions by 329 kg CO_2 eq. In this case, we assumed that the unused 169 m^2 was used to cultivate barley, and therefore reduced the amount of forest and grassland that was converted worldwide to support the increasing demand for barley. We could also argue that the unused 169 m^2 can be changed into grassland or forestland resulting in a different emission factor. It is, however, more valid to assume that the land remained in use of agricultural production and, therefore, does not result in C sequestration. It is, however, difficult to determine the consequences of a change in diet on LUC due to the complexity of the global feed market. Furthermore, it should be noted that Tonini et al. (2012) used an uncertainty of ±170 ton $CO_2 ha^{-1}$, resulting in a high uncertainty when LUC is incorporated in the results.

3.2 Results case study 2: use of beet tails in dairy cattle feed instead of using it as a substrate for anaerobic digestion

3.2.1 Changes in land use

Changes in LU from using 1 ton beet tails in dairy cattle feed instead of using it to produce bioenergy were based on Eq. [2]: $D1a,b-\Delta B1a,b-I1+I2-D2+\Delta B2=1.15-0.11-3.33+0.14-152+0=-154$ m^2 (Fig. 3).

Reducing 1 ton of beet tails to produce bioenergy resulted in an increase of LU from electricity of fossil sources of 0.79 m^2, 0.02 m^2 for heat, and 0.34 m^2 for artificial fertilizer. LU related to the transport of artificial fertilizer was <0.00. ($D1a,b=0.79+0.02+0.34=1.15$ m^2). Using 1 ton beet tails as dairy cattle feed, however, displaced 94 kg DM barley in dairy cattle feed, resulting in a LU of 152 m^2 (*D2*). LU related to the intermediate process of digestion of beet tails (*I1*) was 0.14 m^2 for transport of beet tails, 2.81 m^2 for capital goods, 0.11 m^2 for digestion of beet tails, 0.27 m^2 for storage and transport of digestate, and no LU for burning of bioenergy. ($I1=0.14+2.81+0.11+0.27=3.33$ m^2). LU related to the intermediate process of beet tails fed to dairy cattle (*I2*) was the transport of beet tails, resulting in a LU of 0.14 m^2. LU related to the application ($\Delta B1a$) of the digestate was 0.13 m^2 instead of 0.02 m^2 for artificial fertilizer, resulting in a net LU of 0.11 m^2 ($\Delta B1a=0.13-0.2=0.11$ m^2). No LU was related to $\Delta B1b$ and $\Delta B2$.

This means, in our case study, that land use was decreased with 154 m^2 when 1 ton of beet tails was used in dairy cattle feed instead of using it as a substrate for anaerobic digestion.

3.2.2 Changes in emission of GHGs

Changes in emission of GHGs from using 1 ton beet tails in dairy cattle feed instead of using it as a substrate for anaerobic

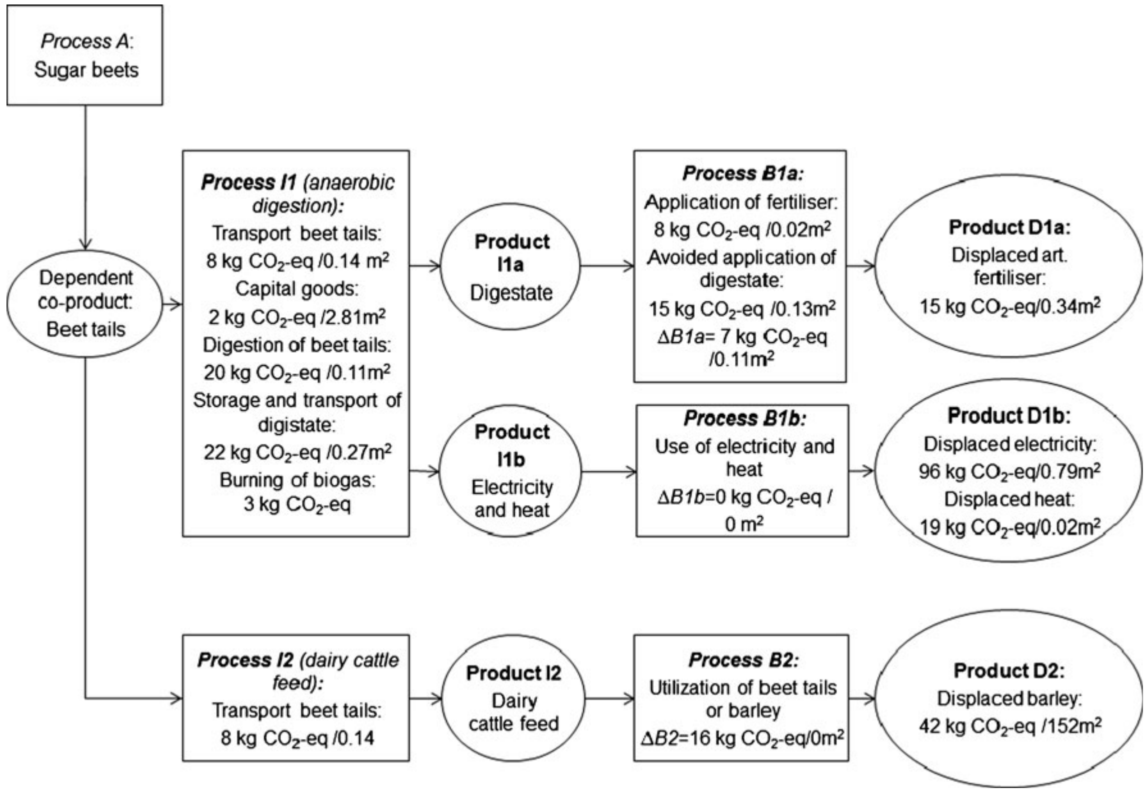

Fig. 3 Processes that are affected by using 1 ton of beet tails as dairy cattle feed instead of using it as a substrate for anaerobic digestion (situation 2, Eq.: $D1a,b-\Delta B1a,b-I1+I2-D2+\Delta B2$)

digestion were based on Eq. [2]: $D1a,b-\Delta B1a,b-I1+I2-D2+\Delta B2=130-7-55+8-42+16=50$ kg CO_2 eq.

Reducing 1 ton of beet tails to produce bioenergy resulted in an increase of 96 kg CO_2 eq from electricity, 19 kg CO_2 eq from heat and 15 kg CO_2 eq from artificial fertilizer. Emissions related to the transport of artificial fertilizer were <0. ($D1a,b=96+19+15=130$ kg CO_2 eq). Using 1 ton beet tails as dairy feed, however, displaced 94 kg DM barley in dairy feed, resulting in a decrease of 42 CO_2 eq ($D2$).

GHG emissions related to the intermediate process of digestion of beet tails ($I2$) were 8 kg CO_2 eq for transport of beet tails, 2 kg CO_2 eq for capital goods, 20 kg CO_2 eq for digestion of beet tails, 22 kg CO_2 eq storage and transport of digestate, and 3 kg CO_2 eq for burning of biogas ($I1=8+2+20+22+3=55$ kg CO_2 eq). GHG emissions related to the intermediate process of beet tails fed to dairy cattle ($I2$) was the transport of beet tails, resulting in 8 kg CO_2 eq. GHG emission related to the application ($\Delta B1a$) of digestate was 15 kg CO_2 eq, and the application of artificial fertilizer was 8 kg CO_2 eq, resulting in 7 kg CO_2 eq. GHG emissions related to feed utilization (i.e. CH_4 from enteric fermentation) was 16 kg CO_2 eq for dairy cattle ($\Delta B2$). The latter value was computed given that 1 ton of beet tails in diets of dairy cattle displaced 94 kg DM barley resulting in emission of 2.09 kg CH_4 (i.e. $94\times22.17/1,000$), whereas 1 ton of beet tail (136 kg DM) resulted in an emission of 2.72 kg CH_4 (i.e. $136\times20/1,000$). Therefore, enteric CH_4 emission increased by 0.63 kg CH_4, resulting in 16 kg CO_2 eq by feeding beet tails instead of barley to dairy cattle.

This means, in our case study, that using 1 ton of beet tails in dairy cattle feed instead of using it as a substrate for anaerobic digestion, increased GHG emissions by 50 kg CO_2 eq. When accounting for GHG emissions from LUC (i.e. $1.22\times1.55\times-152$ $m^2=-290$ kg CO_2 eq), using 1 ton of beet tails in dairy cattle feed instead of producing bioenergy reduced emissions by 239 kg CO_2 eq. However, again, one should take into account an uncertainty of ±170 ton $CO_2\,ha^{-1}$ and, furthermore, we assumed again that the unused 154 m^2 was used to cultivate barley resulting in a reduction of converted forest or grassland.

4 General discussion

4.1 Nutritional requirements

In both cases, we assumed that we could replace the co-products wheat middlings and beat tails by one product (barley) based on the energy content. We based this assumption on the fact that wheat middlings, beet tails and barley are all used for their energy content. Nevertheless, besides energy, there are other nutritional factors which should be taken into account, such as crude protein and amino

acids. Furthermore, in the composition of diets, anti-nutritional factors and taste play a role. Increasing wheat middlings in diets of dairy cattle with 1 kg will most likely result in a decrease of multiple ingredients, including, barley. An in-depth study is needed to analyze the nutritional consequences of changing the amount of co-products, such as wheat middling and beet tails, in diets of livestock. The same applies for the use of co-products to produce bioenergy. Beet tails are generally co-digested with manure and other substrates, but for reasons of simplicity, we focused solely on beet tails as substrate for anaerobic digestion.

4.2 Framework of Weidema et al. (2009) and our extended framework

We based our framework on the theory of Weidema et al. (2009). They described their procedure for dealing with multifunctional processes on the basis of Table 1. They stated that if the demand for the determining product (product A) is increasing and if the co-product is fully used, the processed co-product (product I) will replace product D. An increase in demand for product B, for which the co-product is used, will not result in an increase of *process A* because the production volume remains restricted to the production volume of the determining product (product A). The increased demand for product B, in this case, has to be supplied with product D.

We, however, wanted to assess the consequences of changing the application of a co-product. By doing so, we were able to analyze the optimal use of the co-products wheat middlings and beet tails. We, therefore, assumed that the demand of the determining product and product B remained equal.

4.3 General application of the framework

The framework provides assistance in how to evaluate the environmental impact of changing the application of a co-product. In this article, the focus was on increasing the use of co-products within the livestock sector. The theoretical framework, however, can be used also in sectors outside livestock production. For example, evaluating the environmental impact of changing the application of wood shavings, a co-product produced during the production of laminate, from compost to bioenergy production. It should be noted that depending on the case, different impact categories can be used.

Table 1 Equations for dealing with multifunctional processes, based on Weidema et al. (2009, p15)

Processes affected by a change in demand for:	Product A	Product B
Dependent co-product fully utilised	A+I−D+ΔB	D+B

5 Conclusions

Based on an extended framework, we calculated the environmental consequences of using co-products in animal feed. We included environmental consequences for the alternative application of that used co-product and illustrated this by two cases: using wheat middlings as dairy cattle feed instead of pig feed and using beet tails as dairy cattle feed instead of a substrate for anaerobic digestion. Using wheat middlings in diets of dairy cattle instead of diets of pigs resulted in a decrease of 329 kg CO_2 eq per ton wheat middlings and a decrease of 169 m^2 land. Increasing the use of beet tails in diets of dairy cattle instead of using it as a substrate for anaerobic digestion resulted in a decrease of 239 kg CO_2 eq per ton beet tails and a decrease of 154 m^2 land. This indicates that increasing the use of wheat middlings and beet tails in diets of dairy cattle potentially can reduce GHG emissions and LU. However, emissions from LUC had a significant impact on the results. Excluding emissions from LUC in case 1 ‘wheat middlings’ resulted in a decrease of 9 kg CO_2 and an increase of 50 kg CO_2 eq for case 2 ‘beet tails’. It should, however, be noted that Tonini et al. (2012) used an uncertainty of ±170 ton $CO_2 ha^{-1}$, resulting in a high uncertainty when LUC is incorporated in the results.

Assessing the use of co-products in the livestock sector is of importance as the results of this study show that shifting the application of a co-product can reduce the environmental impact of the livestock sector. A correct assessment of the environmental consequences of using co-products in animal feed should also include potential changes in impacts outside the livestock sector, such as the impact in the bioenergy sector.

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